TES Microcalorimeter Development
NIST/GSFC Collaboration

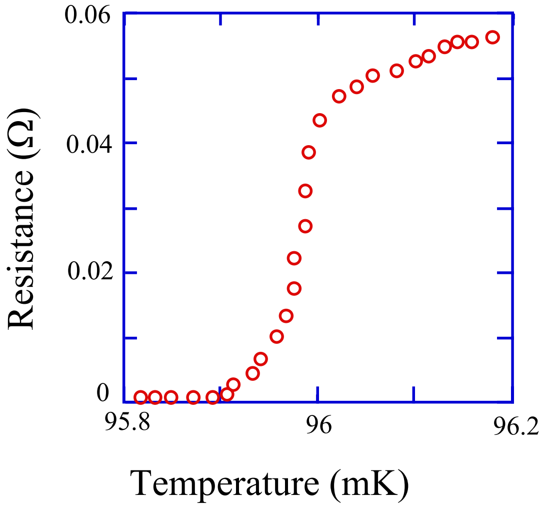
K. R. Boyce, J. A. Chervenak (GSFC), S. Deiker (NIST Boulder), E. Figueroa-Feliciano, F. M. Finkbeiner (GSFC), G. C. Hilton (NIST Boulder), M. E. Huber (CU Denver, NIST Boulder), K. D. Irwin (NIST Boulder), R. L. Kelley, M. A. Lindeman (GSFC), J. M. Martinis (NIST Boulder), S. H. Moseley (GSFC), S. W. Nam (NIST Boulder), F. S. Porter (GSFC), D. A. Rudman (NIST Boulder), R. A. Shafer, C. K. Stahle (GSFC), D. A. Wollman (NIST Boulder)

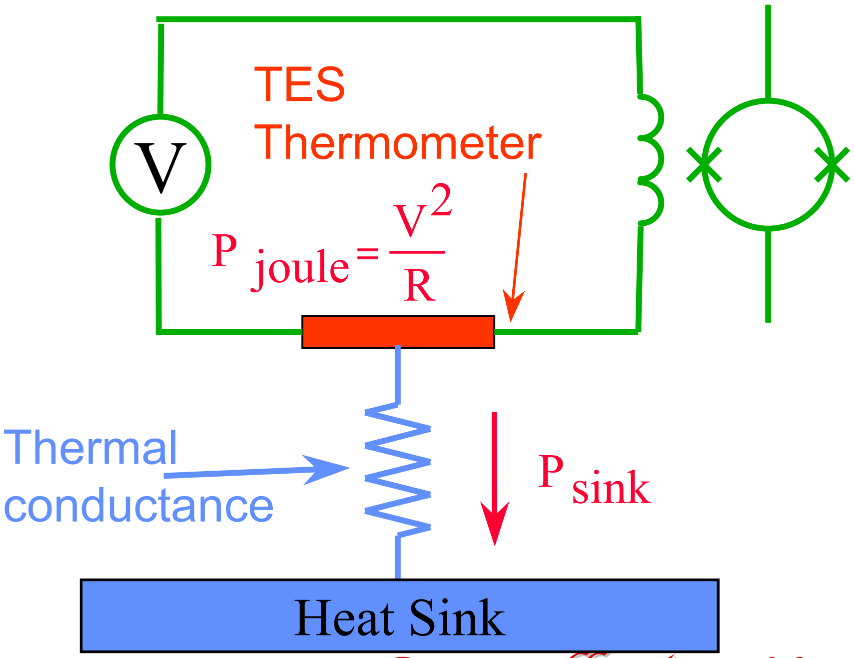
Outline of approach:

- materials and process optimization
- performance optimization
- arrays and their interconnects
- SQUIDs and their multiplexers
- digital electronics

Reminder: Operating Principles

- An x-ray calorimeter consists of a thermalizing absorber, a thermometer, and a thermal link to a low-temperature heat sink.
- In a TES calorimeter, a superconducting film self-biased between the superconducting and normal states serves as the thermometer.
- Since most superconductors undergo the transition to zero resistance at temperatures too high to be of use in a microcalorimeter, it is common to use a bilayer of normal and superconducting films to tune to a particular transition temperature.
- The choice of metals is guided by the need to survive the temperature changes and chemical exposures to which the devices will be exposed in fabrication, as well as optimizing the superconducting properties.





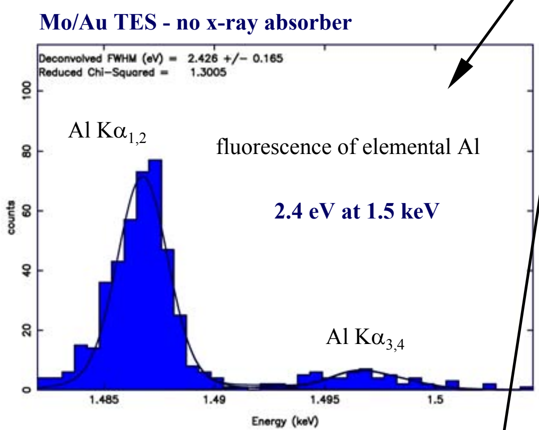
Constellation-X

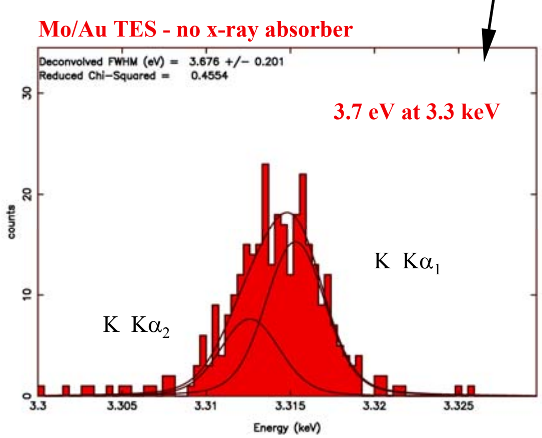
Materials and Processes - different paths

E-beam Mo/Au, Nb leads

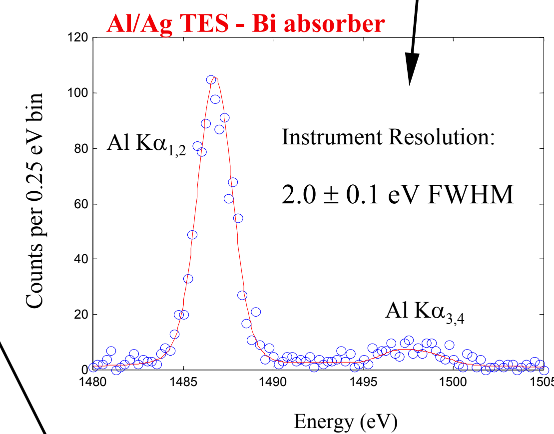
Sputtered Mo/Cu, Mo leads

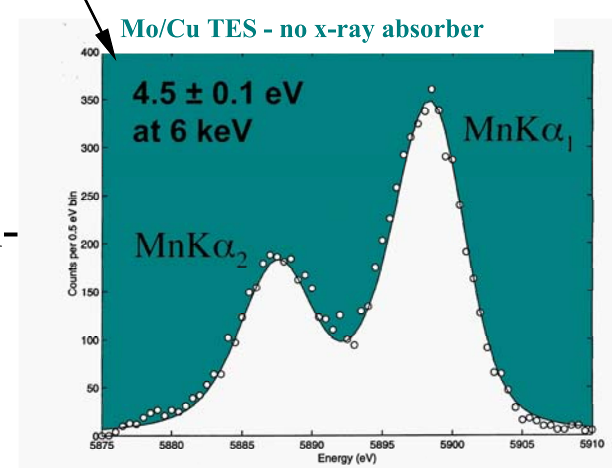
Evaporated Al/Ag





NIST has obtained good results with bilayers of Mo/Cu and Al/Ag. GSFC has done well with Mo/Au. The aluminum-based bilayers have demonstrated electrochemical corrosion, but the molybdenum-based bilayers yield robust devices.





Materials, Processes, and Performance - Open Issues

- Noise:
  - NIST and GSFC see excess noise, but with different scaling
  - need to investigate impact of materials, contacts, shape, volume, and boundary conditions (*e.g. Mo/Cu vs. Mo/Au and undercut Au boundaries vs. normal metal bars*)
  - complete main thrust of investigation in next two years

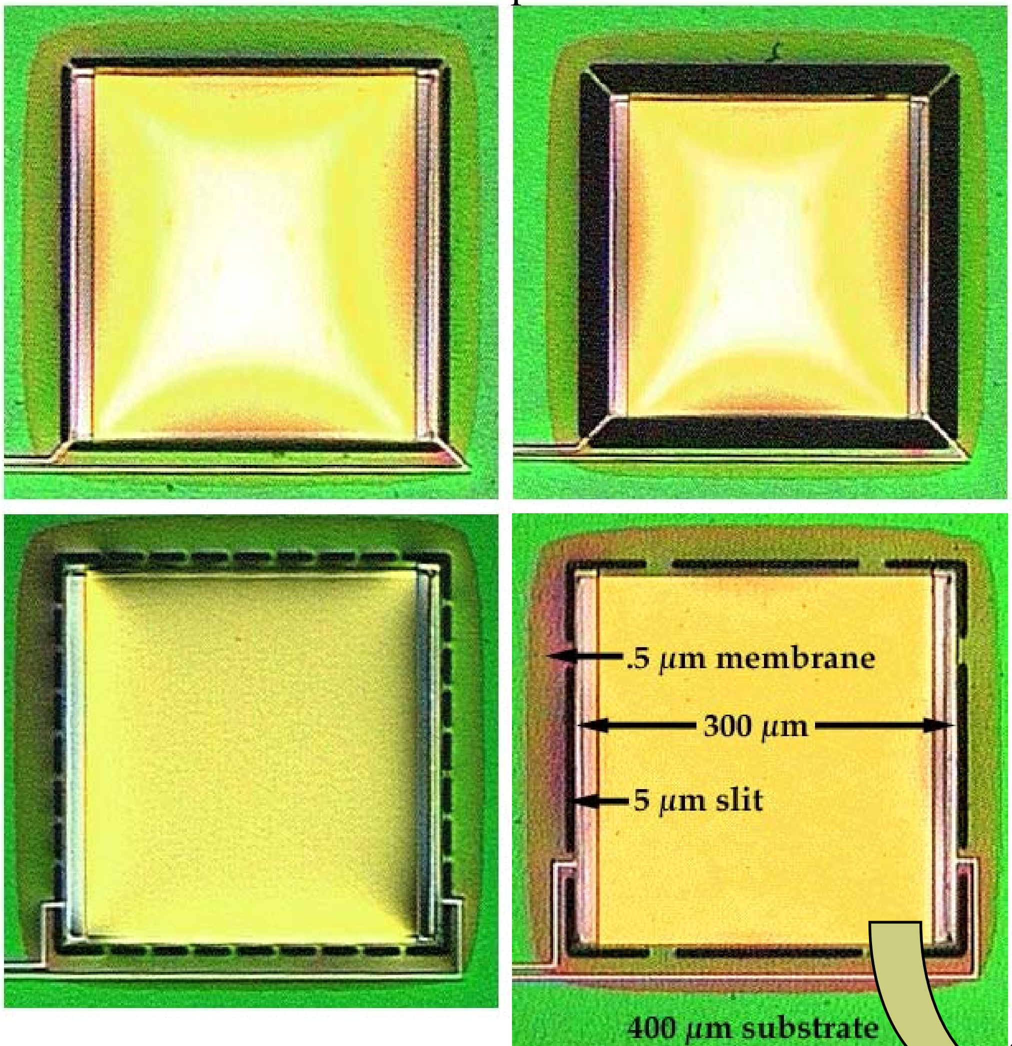
- Reproducibility:
  - new dedicated deposition system at NIST
  - ongoing T_c monitoring at GSFC

- Allocation of heat capacity between TES and absorber in Constellation-X sized pixels

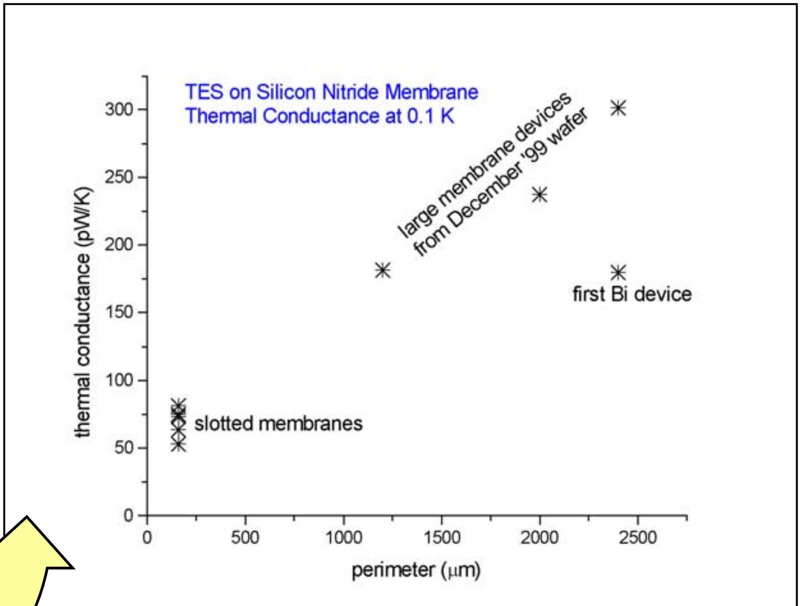
- Absorbers (bismuth + Au or Cu)
  - thermalization
  - confirm no impact on underlying TES superconducting properties

Moving to Arrays

Individual TES devices designed to have different thermal conductance to allow parameterization.

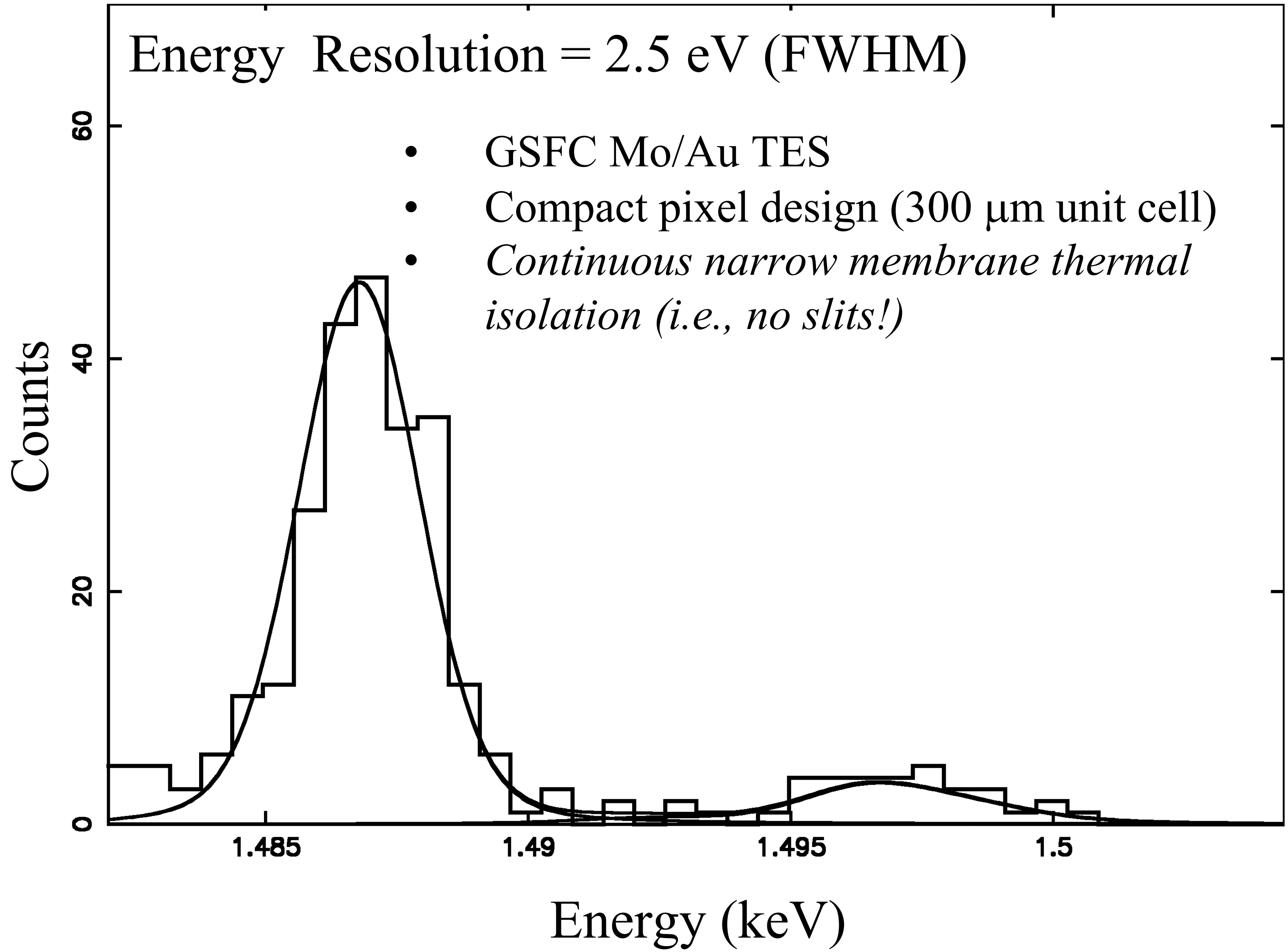


Both NIST and GSFC use silicon-nitride membranes for the thermal link. Initially, these membranes occupied much more area than available for each pixel in the *Constellation-X* array. The present development effort at GSFC is focused on implementing compact pixels in close-packed arrays.



Constellation-X

Latest TES result…



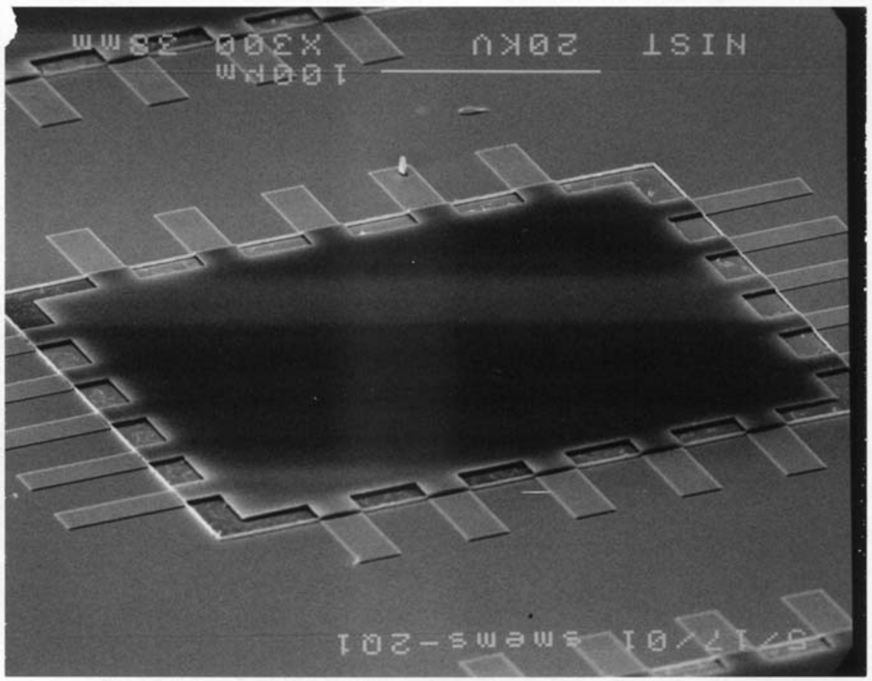
Compact pixel refinement

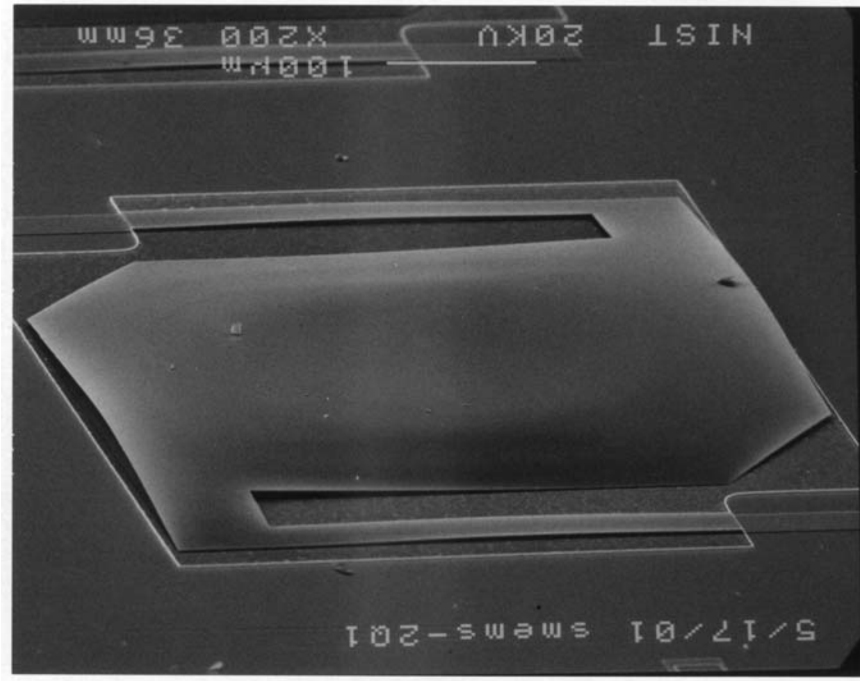
We want a robust, reliable design for the weak link, not overly sensitive to small variations in operating temperature or membrane thickness. Thus, over the next year, we will be measuring G(T) in different geometries for:

- Different nitride thicknesses (0.25, 0.5, and 1.0 microns)
- Different TES T_c

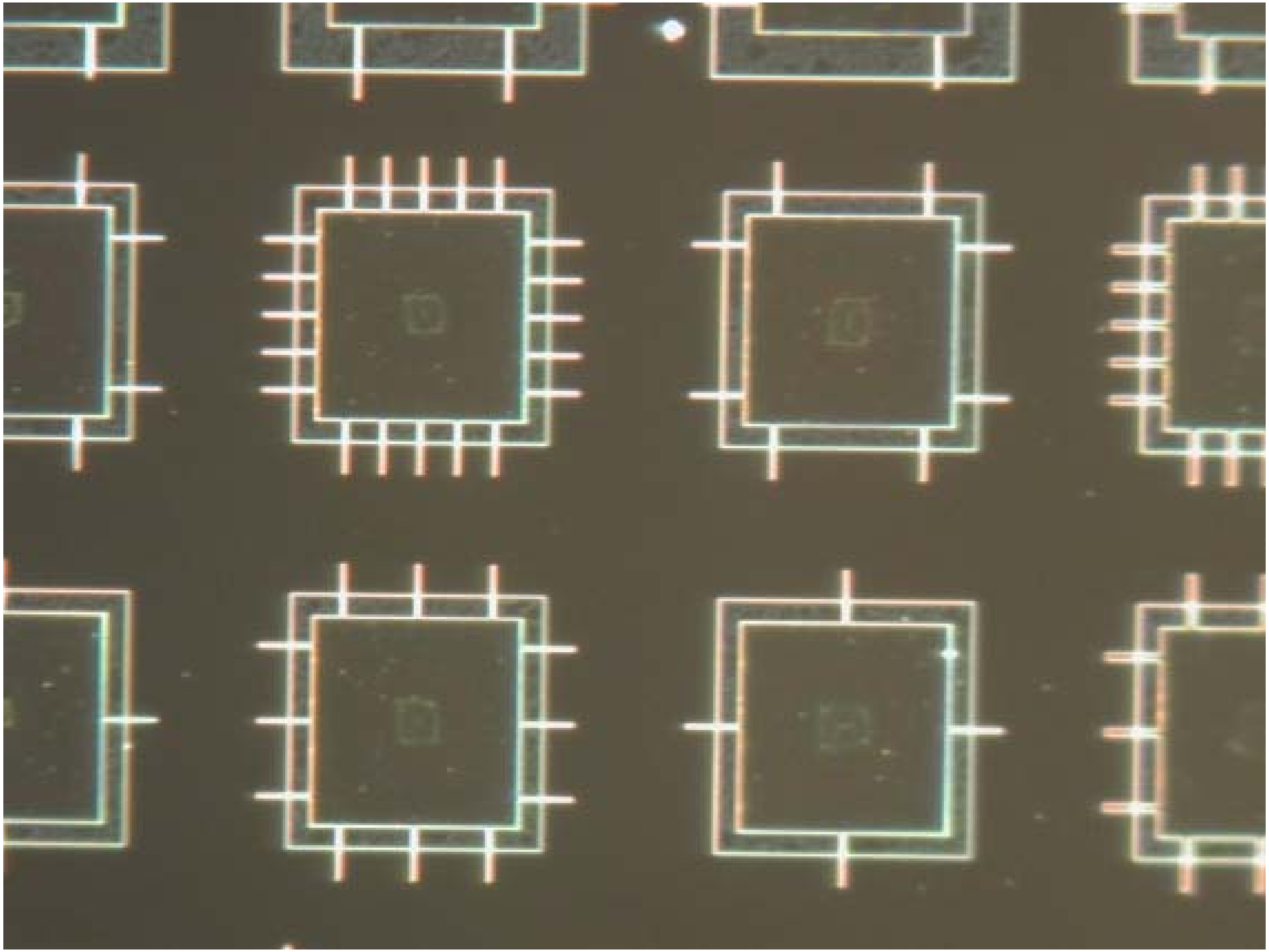
At 70 mK and 0.5 microns we see evidence of phonon mode exclusion, thus extreme sensitivity to temperature and thickness is expected. We likely will have greater control with thicker membranes that have slits than with continuous thin membranes. But we need to do the measurements.

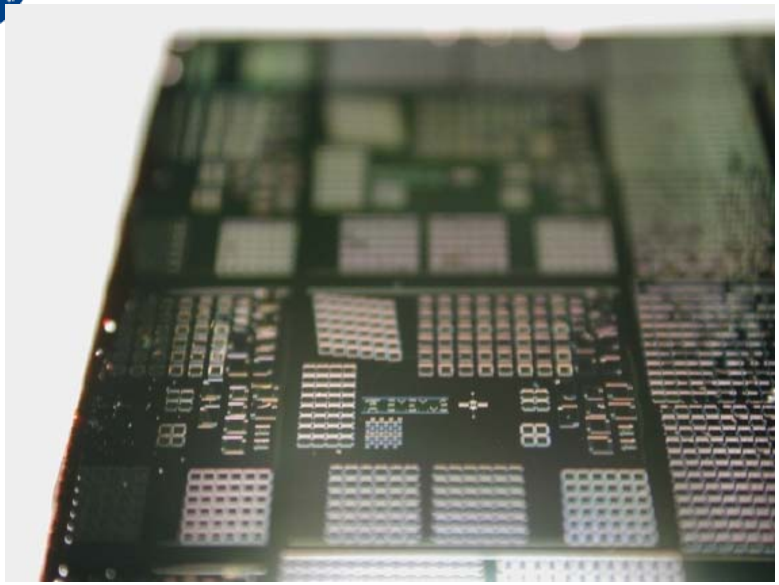
NIST Suspended Nitride Test Structures

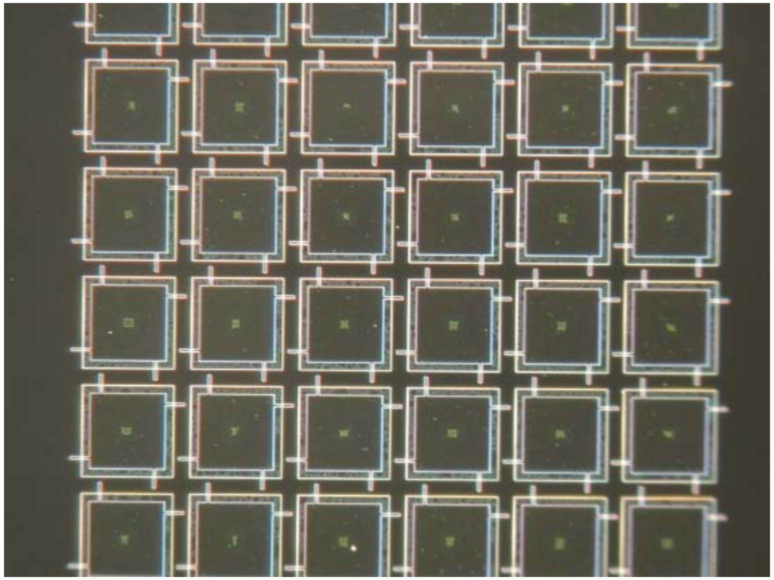


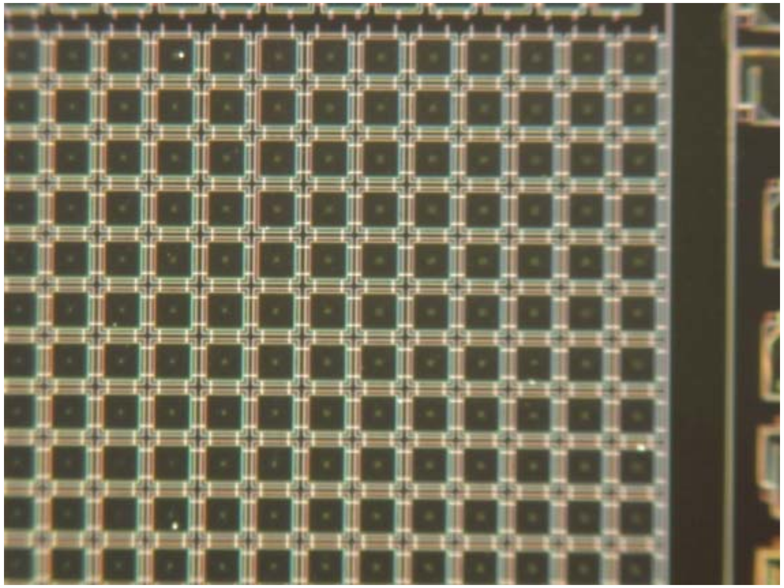


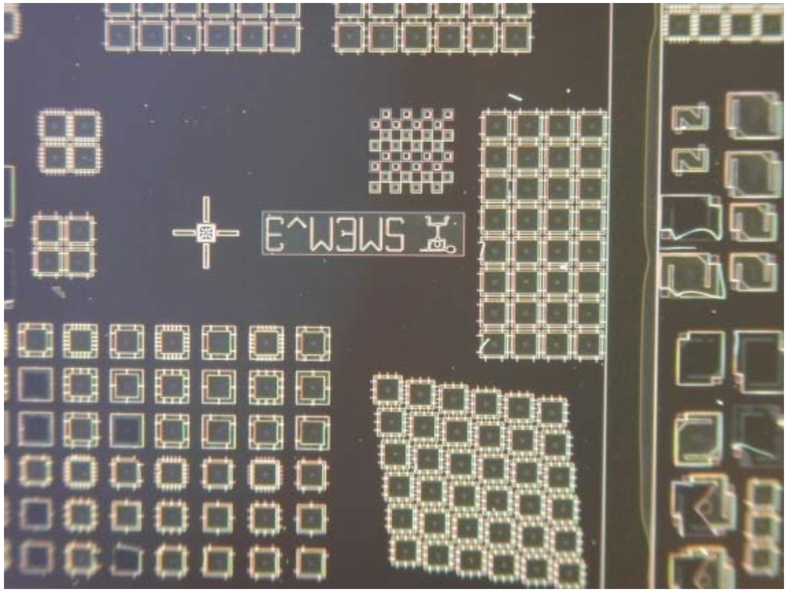
Nitride deposited at NIST over sacrificial polysilicon layer. Idea is to make area under the suspended devices available for wiring traces.





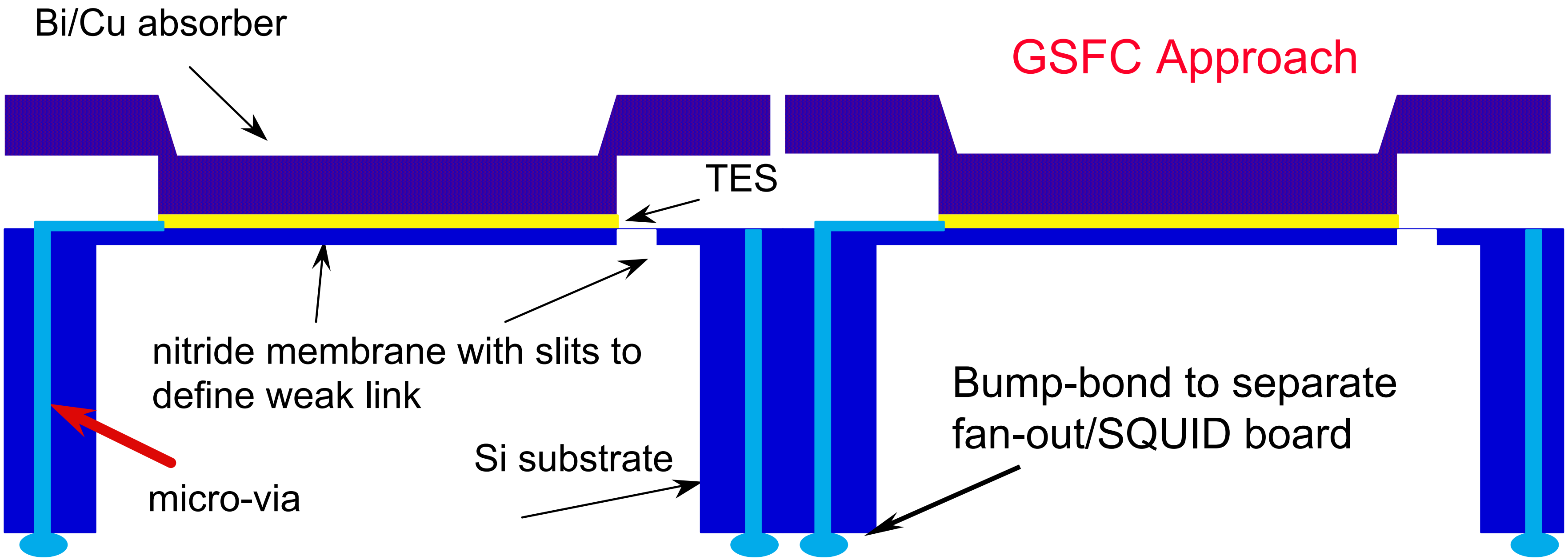


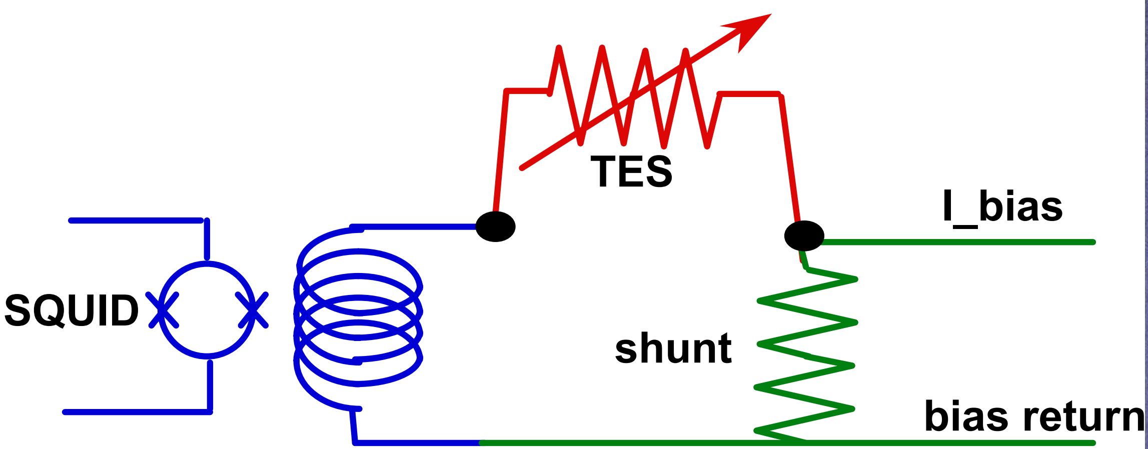


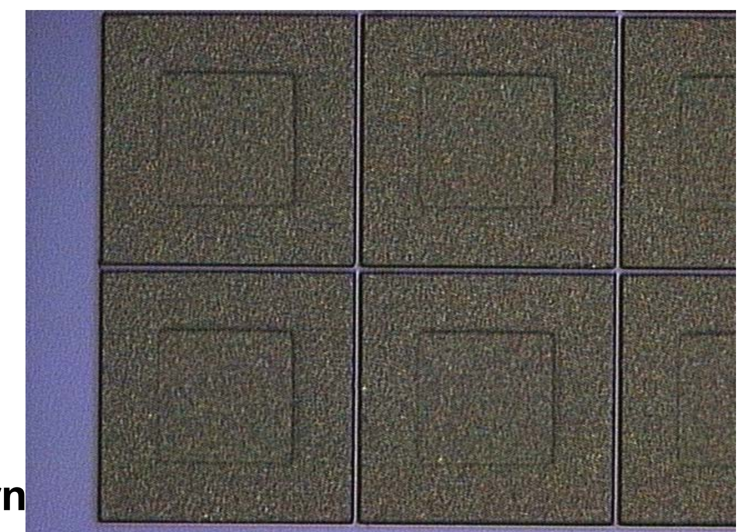


TES Array Concepts

GSFC Approach

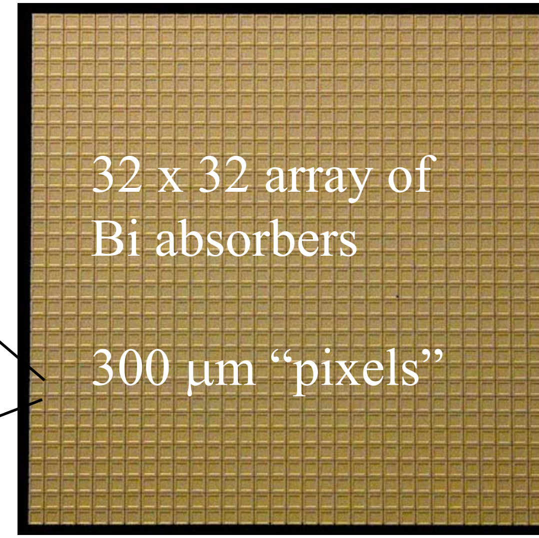


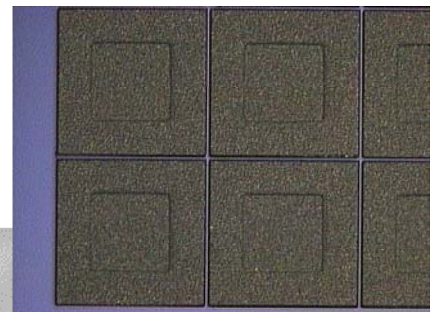


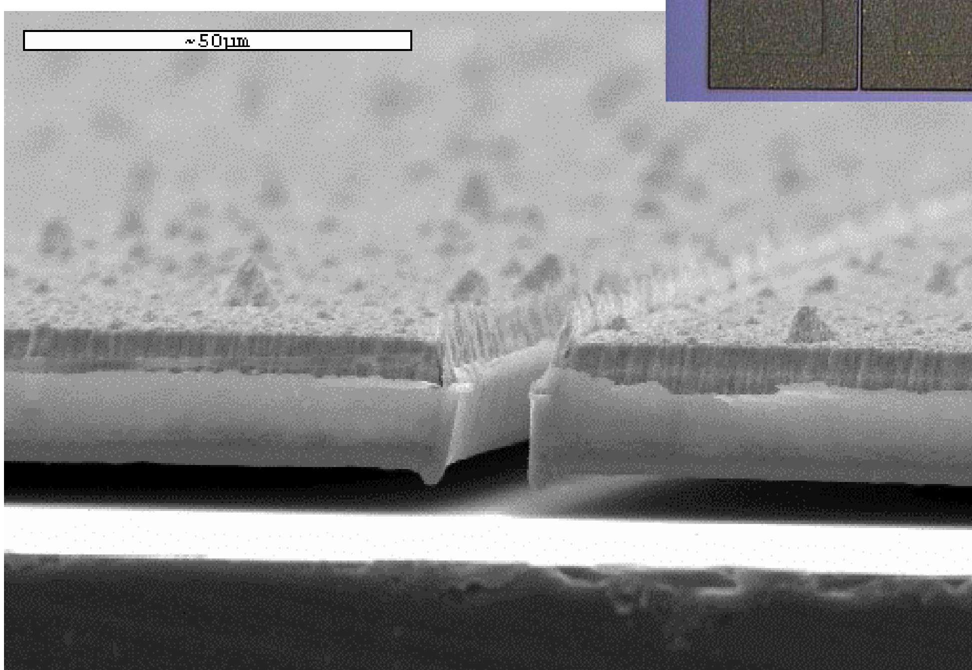


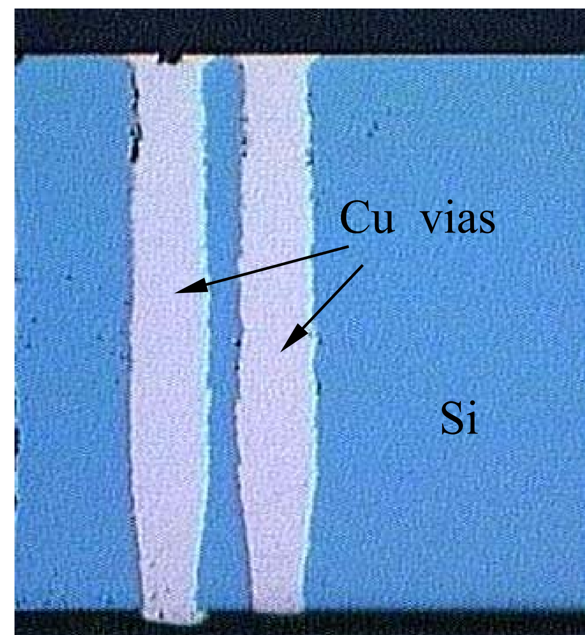
Micromachined Bi Absorbers

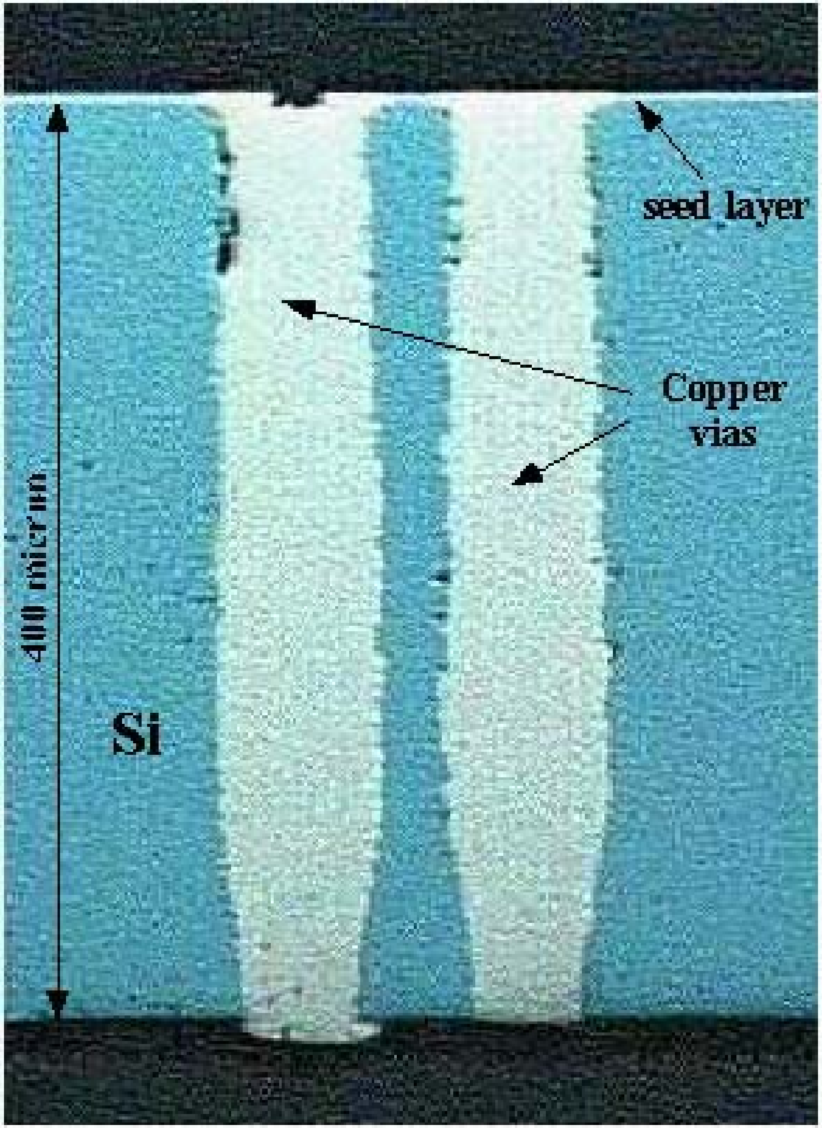
Proof of concept for fabricating x-ray absorbers in array format with high filling factor.



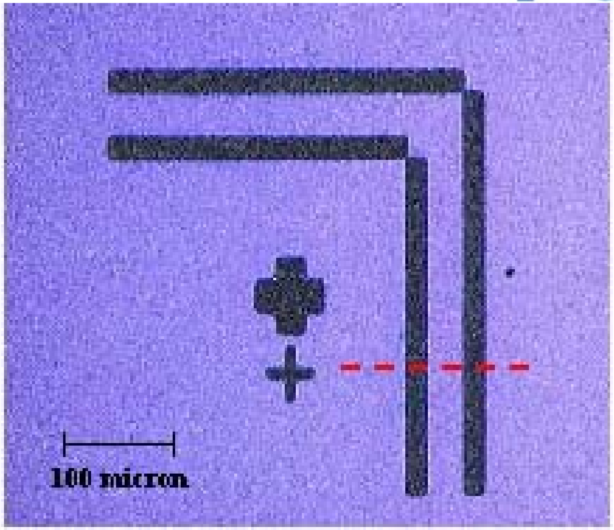




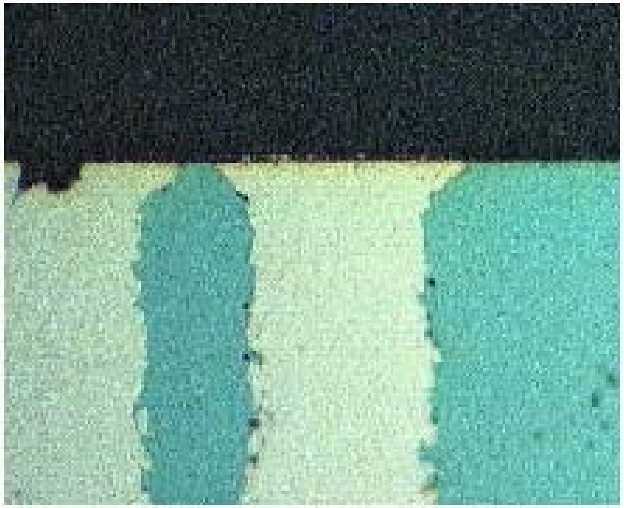




Cross-section of two copper-filled through-wafer vias. The cross-section was taken along the red dotted line in upper right photo.

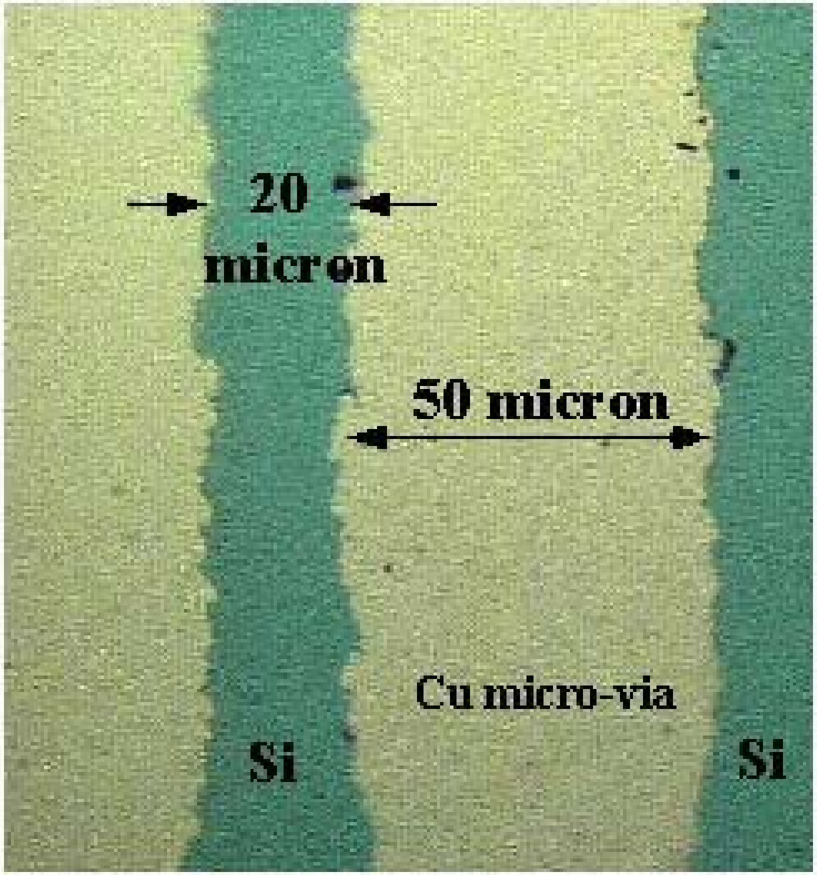


2 pairs of slotted through-wafer vias before filling them with Cu by a standard electroplating process.



Bottom part of Cu vias after removing their Ti/Cu/Au seedlayer.

Cross-sectional view of the upper part of the two micro-vias.



Close-up on Cu micro-vias (cross-sectional view)

Constellation-X

Immediate TES device development plans:

GSFC:

• Almost done with new wafer with compact pixels and higher T_c (120 mK). Half of wafer will have Bi absorbers. Dividing wafer in half along line other axis, half will have the TES boundaries defined by Au bars and half will have the boundary defined by a Mo undercut. Thus we can compare the noise of the 4 permutations, as well as get important data on thermal conductance.

• Thermally cycle vias; measure RRR

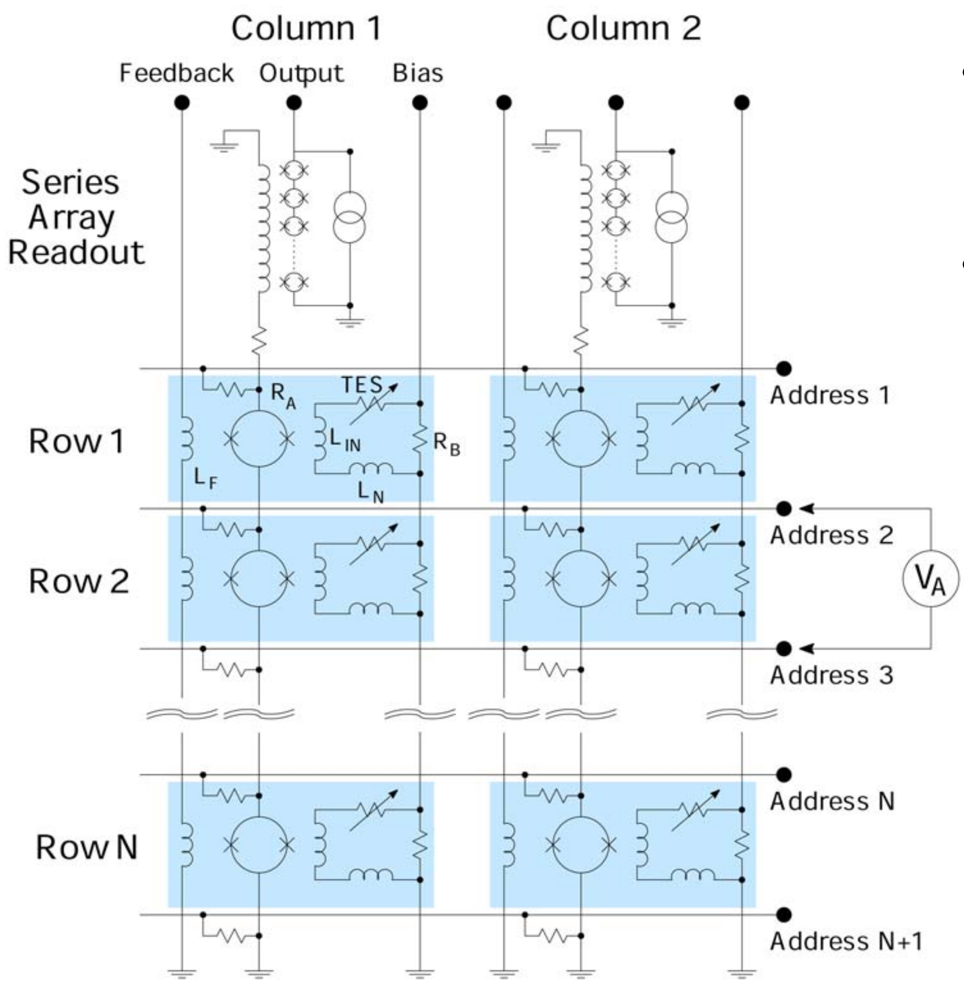
NIST:

• Commission, start using new, dedicated deposition system.

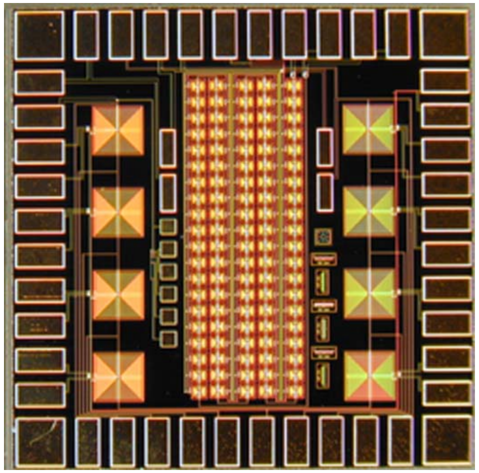
• Perform thermal and electrical tests on surface micromachined structures.

• Fabricate prototype surface micromachined TES pixels.

First Generation SQUID MUX

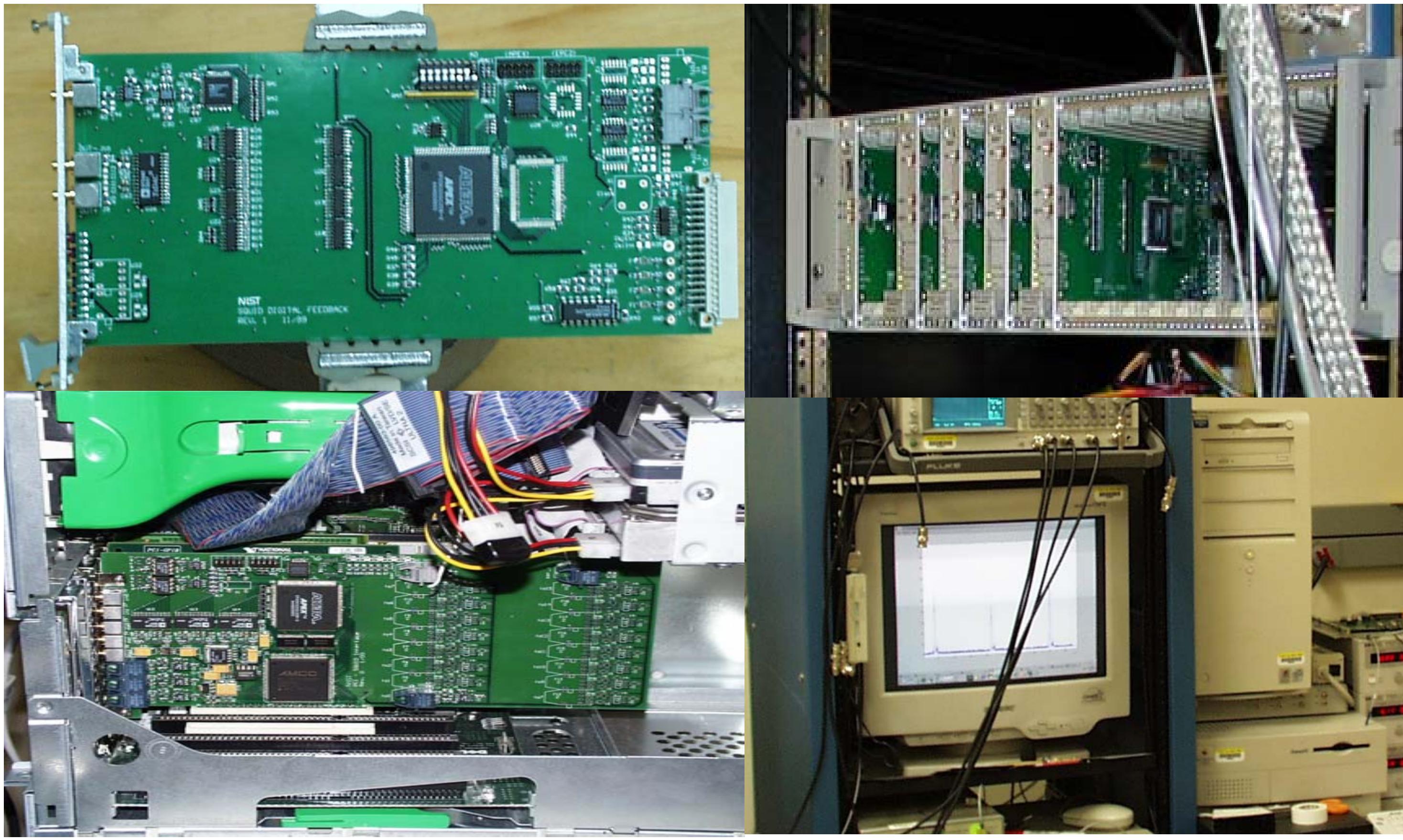


- Initial results at LTD-8: first SQUID MUX for TES readout.
- Voltage applied across two address lines turns on one row of SQUIDs on in ***parallel***.

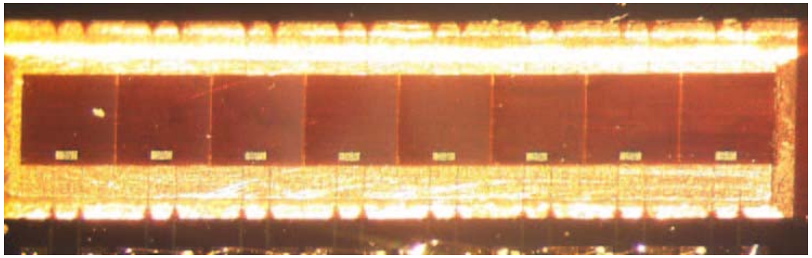


First-generation 8-pixel MUX chip

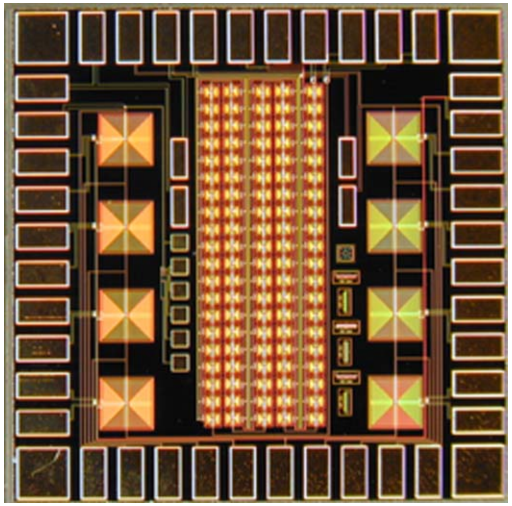
Digital feedback electronics for TDM



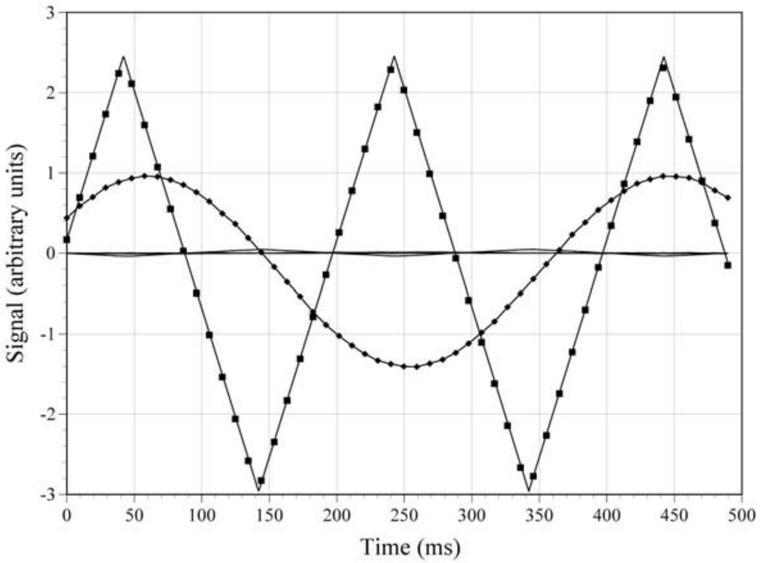
FIBRE: a multiplexed 8-pixel TES bolometer



The TES bolometer array

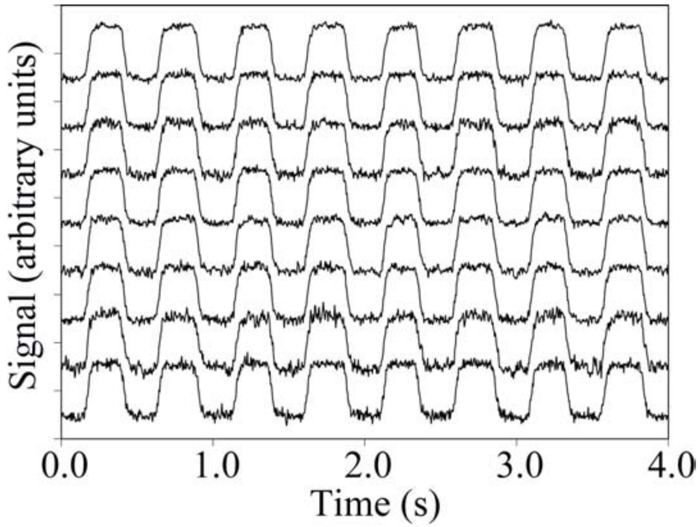


The 8-Channel TDM chip

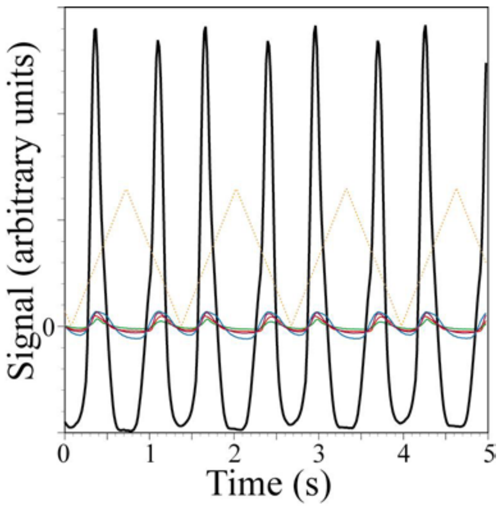


Demultiplexed readout of 8-pixel array with digital feedback and simulated signals. (One sinewave input and one triangle wave input).

FIBRE: optical data

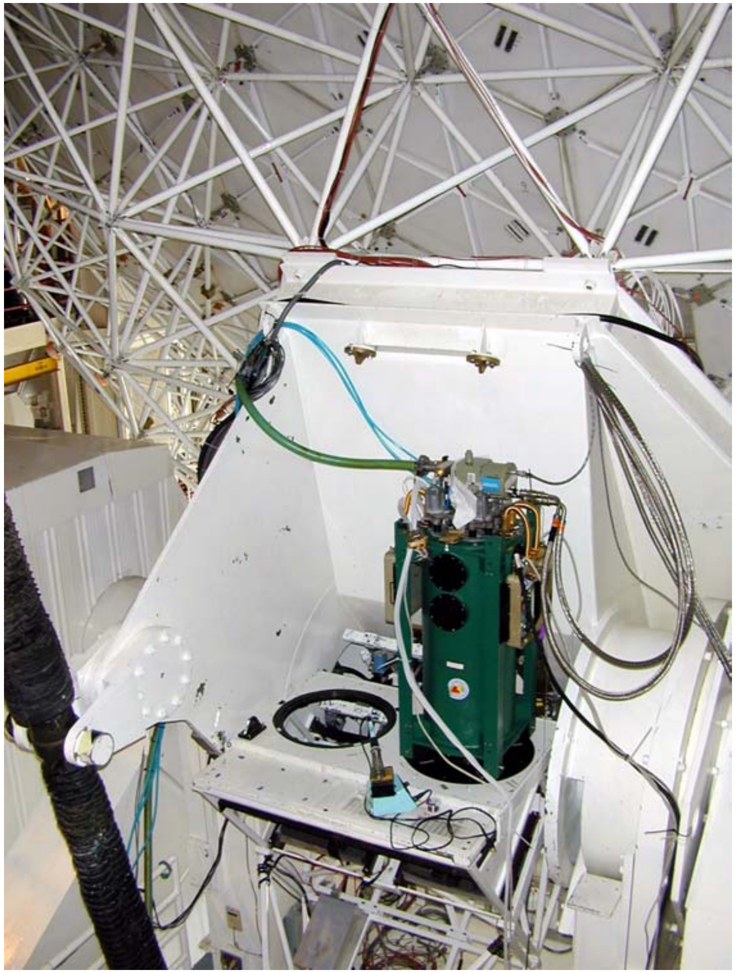


Demultiplexed readout of 8-pixel TES bolometer with chopped bolometric load

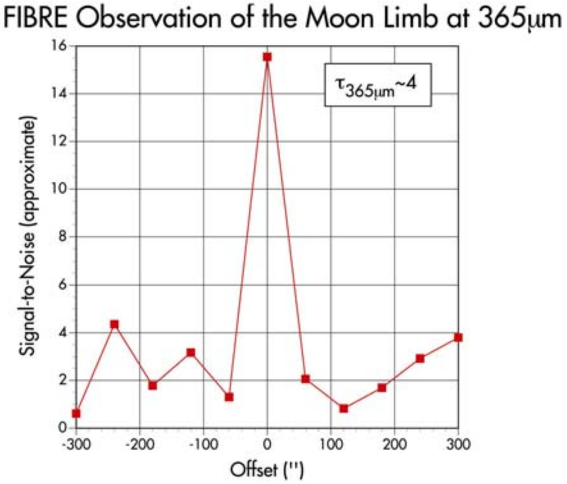


Demultiplexed signal from FIBRE while sweeping the Fabry-Perot (orange) across a local oscillator source with a spectral resolving power of 1200. Only one bolometer channel is in range. Some optical crosstalk evident in ‘off’ channels from Stray light.

FIBRE: astronomical data at CSO



- *Multiplexer operated stably on telescope*
- Photon noise limited
- Dark detector NEP ~ 3 x 10^{-17} W/$\sqrt{\text{Hz}}$ consistent with theoretical phonon noise.



The weather was too poor during the observation window to see galactic sources, so the moon was observed at spectral resolving power of 1200.

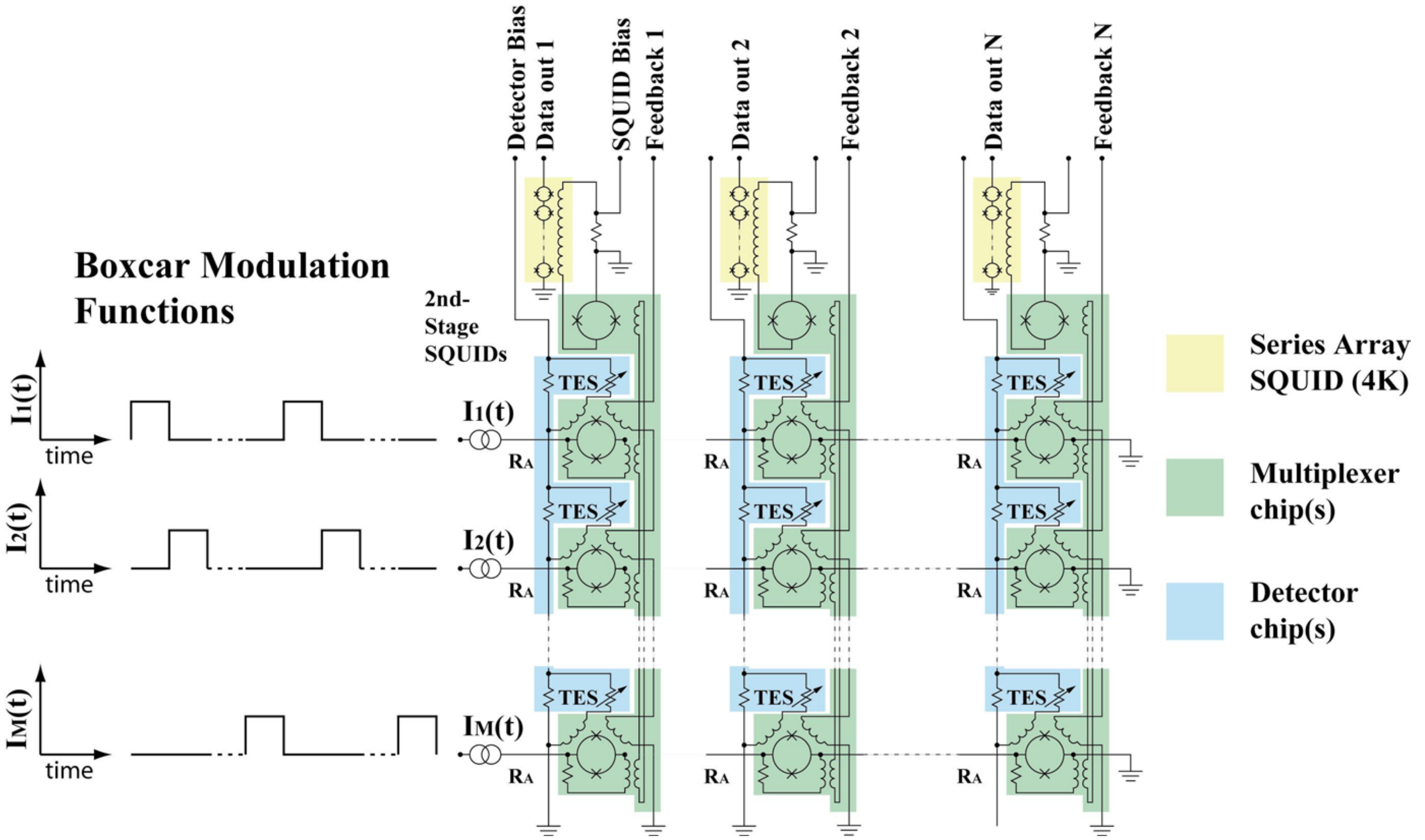
Constellation-X

Problems with First-Generation TDM

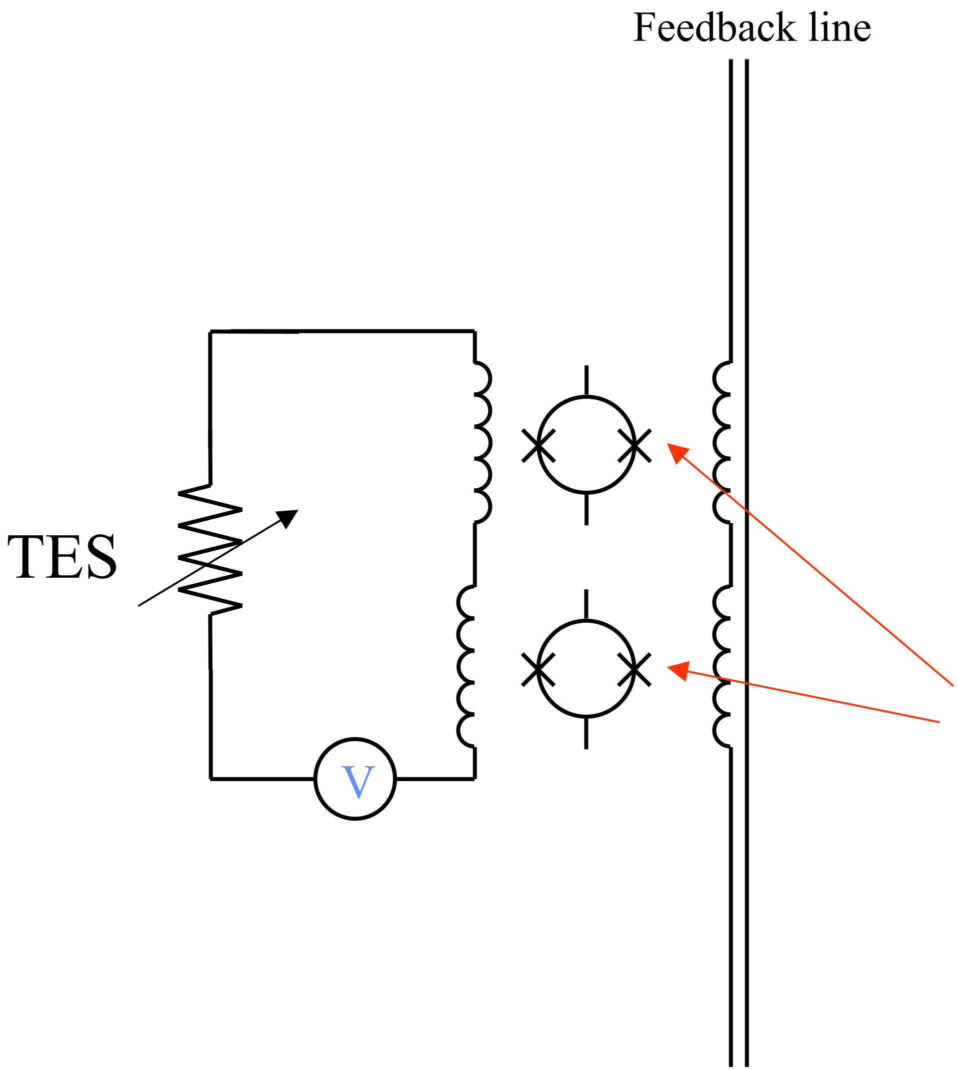
- In order to prevent parasitic currents flowing through the wrong paths in the parallel-addressing configuration, the address resistors have to be made large (~ 100 Ω). This led to high address current, high power dissipation, and address-line crosstalk.
  -> series address circuit

- The coupling of the common feedback coil to the input circuits of the 'off' SQUIDs is an important crosstalk mechanism at high switching rates.
  -> eliminate feedback-input coupling with 'balanced' SQUIDs.

Time-Division SQUID Multiplexer

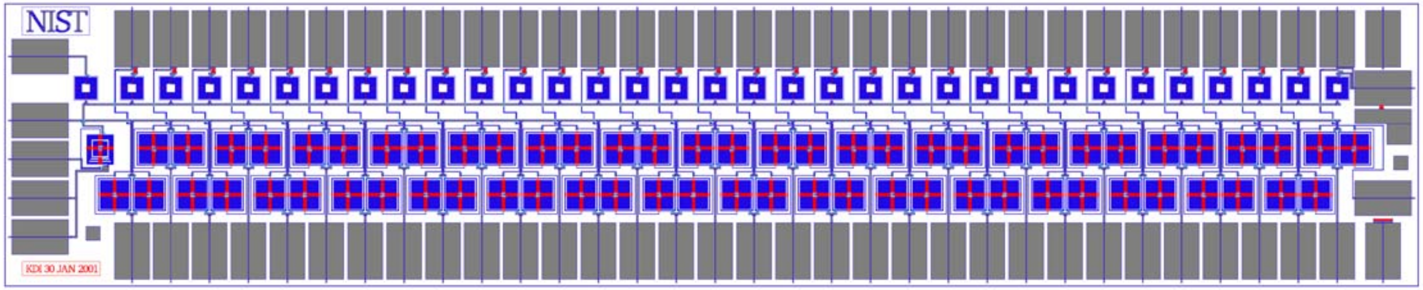


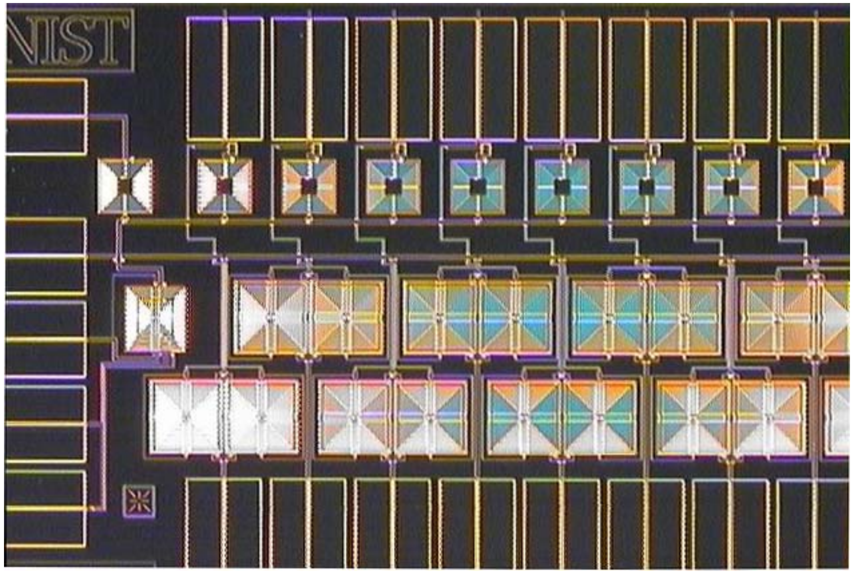
Balanced SQUID Pairs



Feedback to the pixel which is 'on' charges up the input inductors on 'off' pixels: a crosstalk mechanism for *distant* pixels

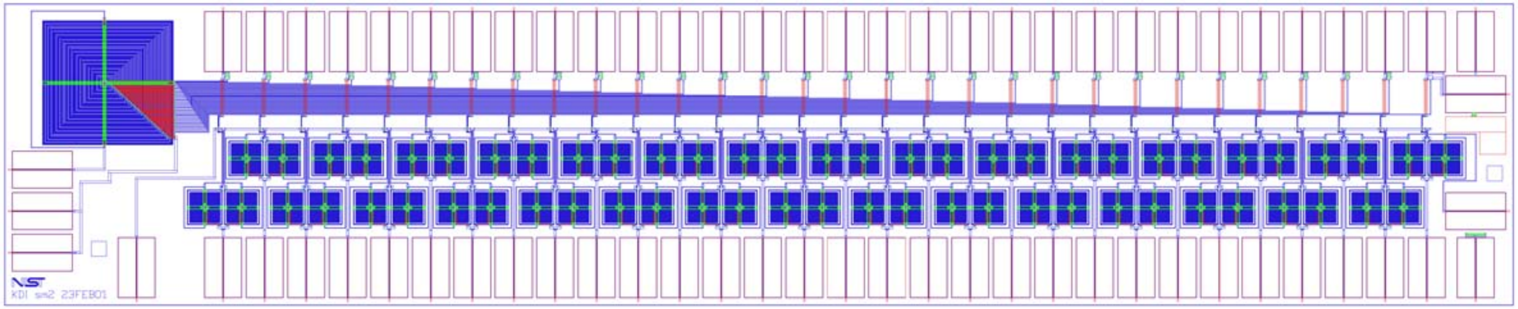
A balanced SQUID pair with opposite winding geometrically cancels this effect. Only one SQUID is turned on: the other is just a dummy.

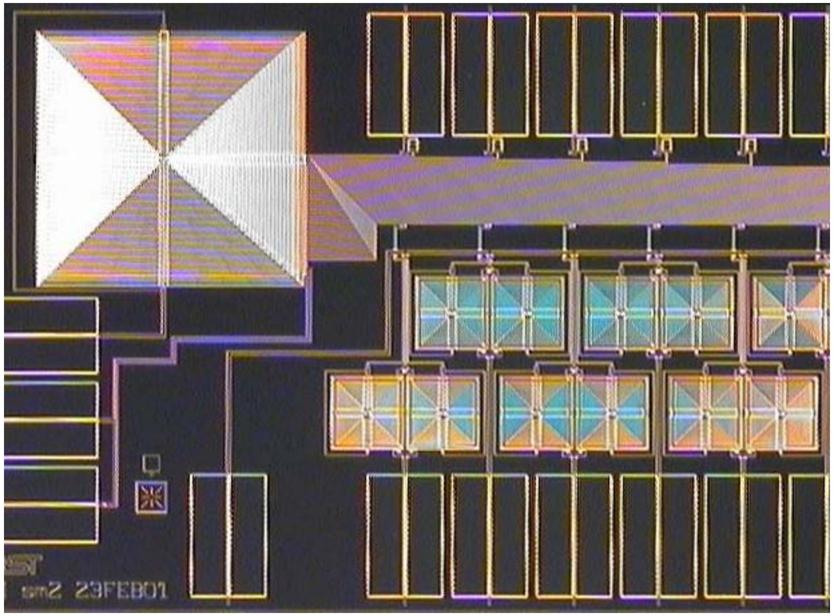




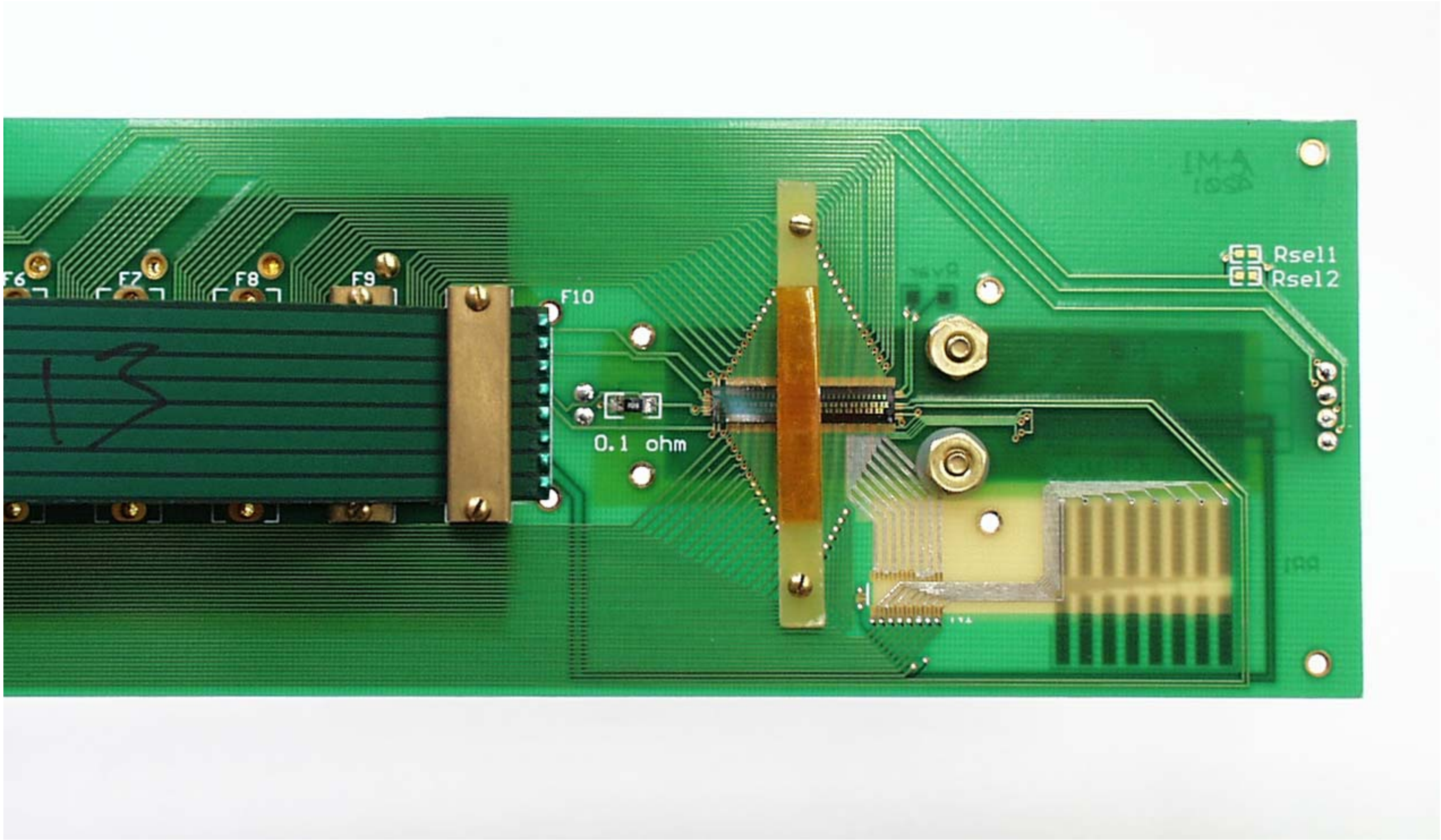
- 1x32. Need 32 chips to instrument kilopixel array.
- Series Addressing – low xtalk, low power (~ 1μW for 32 x 32).
- Balanced SQUID input to zero feedback-input coupling xtalk

32 x N Multiplexer with Individually Coupled 2nd Stage

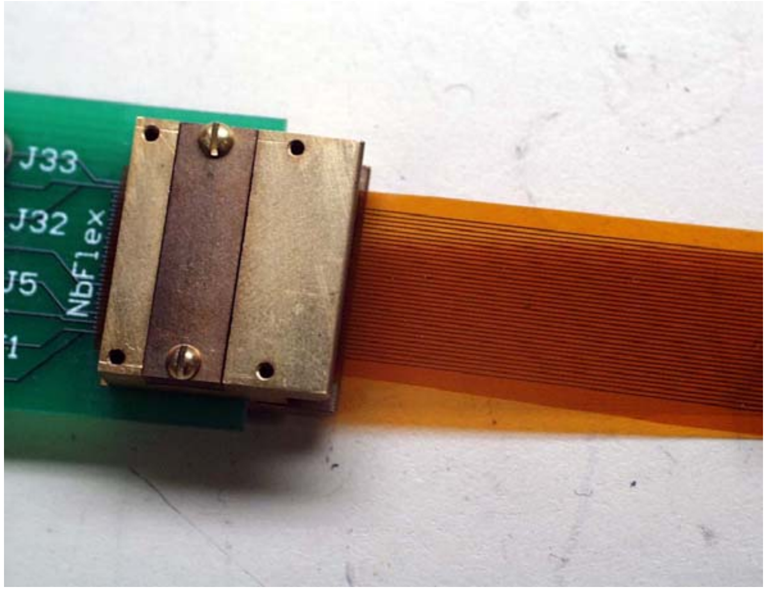




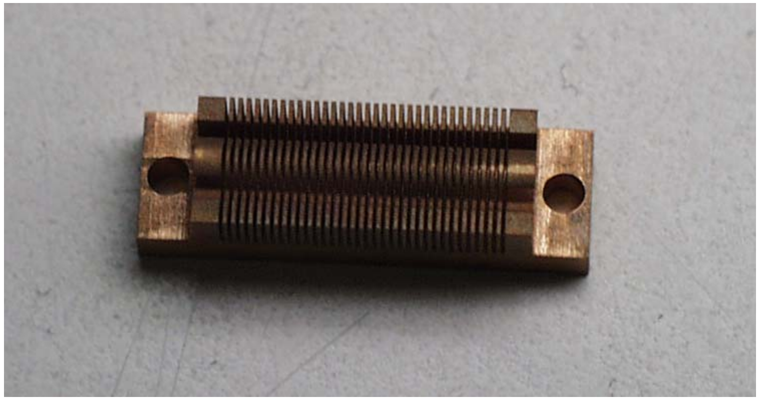
MUX Board



Nb Flex (0.1 K - 4 K)

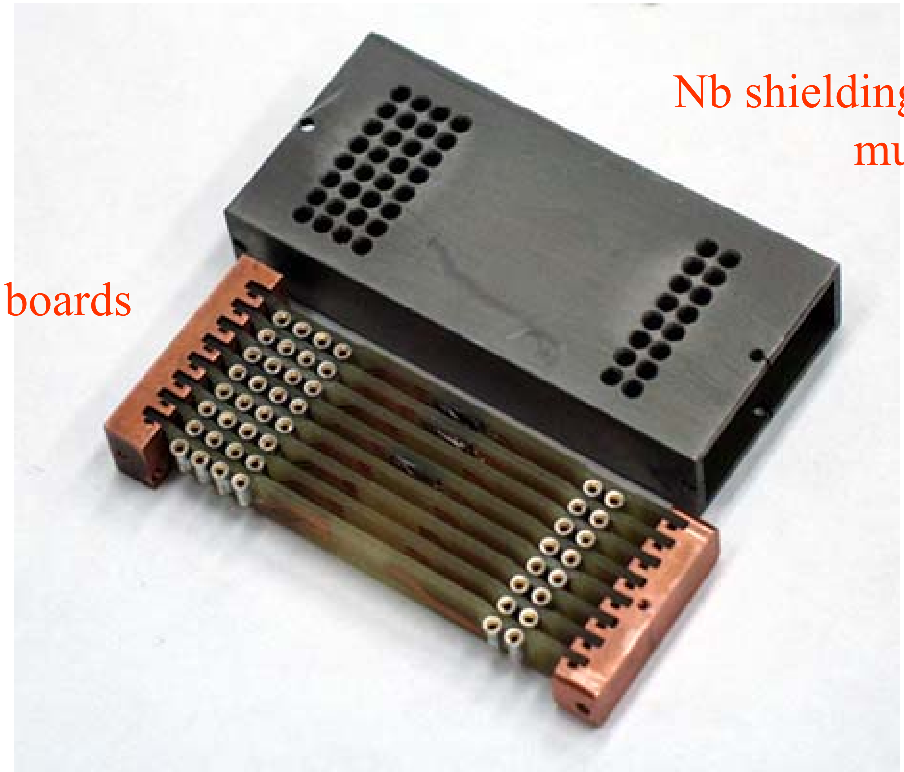


Nb Flex



Be-Cu springs for Nb flex connector

SA SQUID Module



8 modules required for 32 x 32 multiplexed array

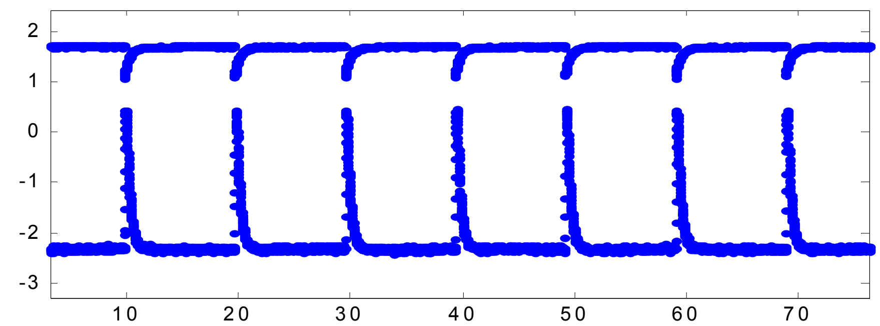
Cu-Ni Flex 4K - 300 K

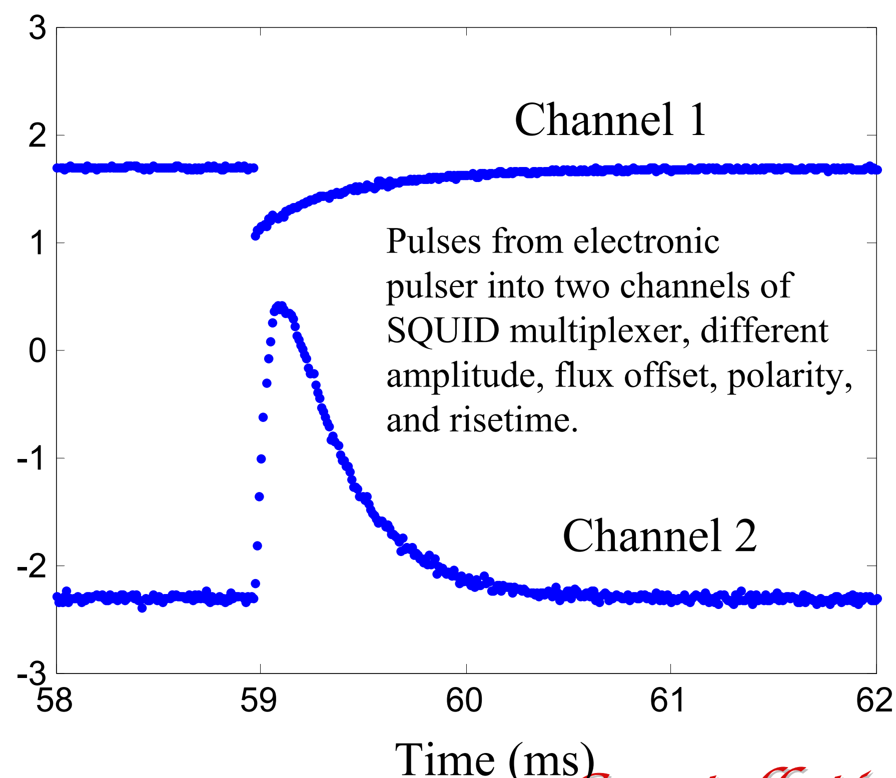
8 flex, each with 16 conductors
(8 signal, 8 return)

Results with 2nd generation 32-channel SQUID MUX

Currently being tested

- Performance stable
- Noise looks good
- ~16 channels tested, all look good.
- Operation at ~500kHz demonstrated - improving
- Need to implement switched digital feedback





SQUID MUX Crosstalk

Nearest Neighbor:	~ 0.25 %
Next nearest neighbor:	~ 0.025 %

This does *not* include optical or thermal crosstalk, or crosstalk in the input circuit - only the crosstalk in the SQUID multiplexer itself.

Line rate requirement for 100us response time

Noise aliasing

Signal band 1/(2*pi*100us) = 1.6 kHz

L/R band ~ 10 kHz

Nyquist sample rate ~ 20 kHz

32 pixels ~ 600 kHz

x2 noise margin ~ 1.2 MHz

Arrival time determination

Con-X response time goal ~ 100 us

Sample 20x on fall, 3x on rise ~ 5 us

Multiplex 32 pixels ~ 150 ns

Line Rate: 6.4 MHz